

Fast-Flow Underfill Encapsulant: Flow Rate and Coefficient of Thermal Expansion

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Abstract— In the flip-chip on board assembly method, an underfill encapsulant material is applied in the gap between the integrated circuit (IC) chip and substrate to distribute the shear stresses at the solder interconnects. These shear stresses are imposed on the solder interconnects due to a coefficient of thermal expansion (CTE) mismatch between the IC chip and substrate. Different technologies such as fast-flow, no-flow, and reworkable underfills are currently being studied for flip-chip underfill encapsulant materials. This paper looks at the underfill encapsulant used in the fast-flow method of underfilling the IC chip/substrate gap. The effect of filler loading, particle size, and particle size distribution on the flow rate and CTE of the fast-flow underfill material are discussed in this work. The material used for the experiments is an epoxy resin with added silica filler to decrease the CTE. This study focuses on what effect different filler characteristics have on the underfill encapsulant. Also, an underfill encapsulant that can compete with one of industry's faster fast-flow underfills was developed as a result of this work.

Index Terms— Flip-chip, flow rate, silica, TCE expansion, underfills.

I. INTRODUCTION

TWO significant limitations in state-of-the-art flip chip on board assembly technology are the long processing times required for flow of the underfill and the long times required for underfill cure. Also, this underfill is required to closely match the CTE value of the solder to minimize the stresses brought about by the thermal mismatch between IC chip and substrate on the solder/IC chip and solder/substrate joints. This also requires good adhesion of the underfill encapsulant to both the IC chip and substrate.

The underfill encapsulant is normally applied to one or two sides of the IC chip during dispensing. Capillary flow drives the underfill under the IC chip to completely fill the IC chip/substrate gap. Many factors can play a role in the rate of flow of the underfill encapsulant in the gap. These factors can be placed into four categories:

- 1) filler particles;
- 2) underfill material;

- 3) IC chip/substrate surfaces;
- 4) obstructions.

The filler particle factors that can effect rate of flow include loading, size, size distribution, surface morphology, shape, material, density, and dispersion. The underfill material factors include temperature, rheology, density, and surface tension. The IC chip/substrate surface factors include temperature, surface energy, and roughness. Obstruction factors can include solder bump pattern, particle size to gap height ratio, and contamination. Many papers have been written concerning the flow of underfill encapsulants in flip-chip assemblies [1]–[6].

A CTE value of 20–40 ppm/°C is required to reduce the stresses in the flip-chip assembly [6]. The CTE is lowered by increasing the filler loading, but this also increases viscosity. A higher viscosity leads to a lower flow rate. Therefore, it is important to determine how to achieve a low CTE while keeping a low viscosity. Also, due to the decrease in flow rate with increasing IC chip size and decreasing gap size, the need for studying the characteristics of flow arises. This work focuses on increasing the flow rate of the underfill between the chip and substrate by studying the affects of filler loading and particle size on CTE and flow properties.

II. EXPERIMENTAL

A. Chemical Ingredients of Samples

The epoxy resin used is 3,4-epoxy cyclohexyl methyl-3,4-epoxy cyclohexyl carboxylate, manufactured by Union Carbide under the trade name ERL-4221D (used as received). The molecular weight is 252.3 g/mol and the epoxy equivalent weight is 133.0 g. The hardener used is hexahydro-4-methylphthalic anhydride (HMPA), purchased through Aldrich Chemical Company, Inc. (used as received). The HMPA has a purity of more than 97% and its molecular weight is 168.2 g/mol. The curing catalyst used is a metal acetylacetonate (used as received). The filler used is spherical fused silica with average particle diameters of 8, 15, and 30 μm .

B. Preparation of Filled Underfill

The specified quantity of epoxy resin and hardener were stirred together for approximately 2 h. A specified quantity of catalyst was then added to the resin/hardener mixture and stirred for an additional 2 h until the catalyst was homogeneously dispersed. The filler was placed in a vacuum oven at

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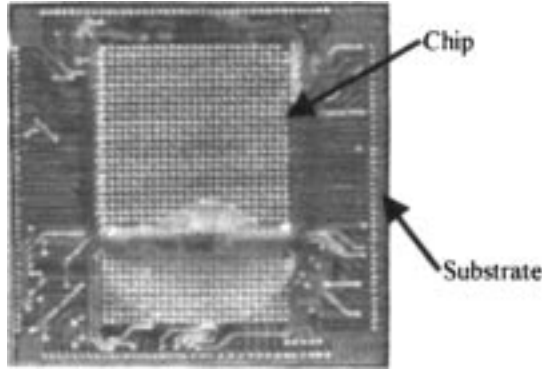


Fig. 1. Flip-chip/substrate test vehicle (624 bumps quartz chip).

120 °C for approximately 24 h. This is to ensure the filler is free of absorbed moisture. The specified amount of filler was added to the resin/hardener mixture in a mixing cup. This mixture was then mixed using a Waring high shear commercial blender at low speed while pulsing. After mixing, the sample was placed in a vacuum chamber and the vacuum pressure was ramped slowly to 27 in Hg over a period of 1 h. This was done to remove the entrapped air introduced into the sample during mixing. The samples were stored in a freezer at -40 °C while not in use.

C. Flow Rate Between Parallel Glass Plates

The flow rates of the resin/filler mixtures were measured using a parallel plate flow test. This test involved flowing the underfill between two glass plates separated by a 3 mil gap at a 12 mm width. The glass plates were pre-cleaned using isopropanol. They were then preheated to 80 °C to aid in reducing the underfill viscosity during flow, to increase the repeatability of the test, and to mimic the actual production underfill dispensing process. A graduated ruler with millimeter markings was placed on top of the top plate as a tool for measuring the flow distance. The distance of flow was timed cumulatively at regular distance intervals.

D. Flow Rate Between Chip/Substrate Test Vehicle

A test vehicle was used to test flow rate *in situ*. This test vehicle was provided by National Semiconductor Corporation (Santa Clara, CA.) It consists of a copper substrate with a solder (eutectic Pb/Sn) pad grid and a 6 × 6 mm transparent quartz simulated chip with a solder bump grid (Fig. 1). The substrate and chip were cleaned with isopropyl alcohol. The vehicle was preheated to 80 °C and approximately 0.02 cc of underfill encapsulant was placed along one edge of the test chip. The time taken to underfill the entire chip was recorded.

E. Coefficient of Thermal Expansion

Coefficient of thermal expansion (CTE) readings of the resin/filler samples were measured using a thermomechanical analyzer (TMA) from TA Instruments (Model 2940). Specimen were made for TMA by dispensing the underfill samples into aluminum pans that were 7 mm dia. × 2.5 mm ht. These pans were then placed into a convection oven at room

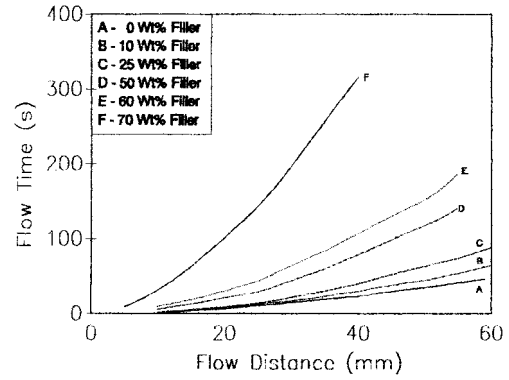


Fig. 2. Flow rate as function of filler loading (15 μm average particle size used for each sample).

temperature, heated to 250 °C, held at 250 °C for 15 min, and then removed to cool at room temperature. The TMA was programmed to heat the samples to 280 °C at a rate of 3 °C/min. The coefficient of thermal expansion was obtained from the slope of the thermal expansion versus temperature plot.

F. Rheology

Rheology of the underfill encapsulant was measured using a Rheolyst AR-1000N from TA Instruments. Tests were conducted at 25 °C using 4 cm steel parallel plates at a gap setting of 150 μm. The shear rate was ramped from 0 1/s to 1000 1/s and then back down.

III. RESULTS AND DISCUSSION

A. Flow Rate

A particle consists of a mass which requires a certain amount of force to give the particle a momentum. This can be seen from

$$P = mv \quad (1)$$

where P is the momentum, m is the particle mass, and v is the velocity. If (1) is written as

$$v = \frac{P}{M} \quad (2)$$

and M is taken as the total mass of a set of particles, it can be seen that when the total mass increases, the velocity will decrease. This is also true of filler particles in the pre-cured underfill matrix (resin) when the total mass of particles is taken as the filler loading and the velocity is taken as flow rate. The force from the matrix to give the filler particles a momentum is acquired from the driving force given by the surface tension at the underfill front. Fig. 2 shows the results of the flow rate as a function of filler loading. As the loading increases, the flow time increases and hence the velocity decreases.

Work conducted by Farris [7] with monodispersed particles showed that particle size has no effect on relative viscosity. Also, Van Der Werff [8] reported that particle size has no effect on relative viscosity through the whole range of volume fractions of particles in fluid. The same conclusion was made

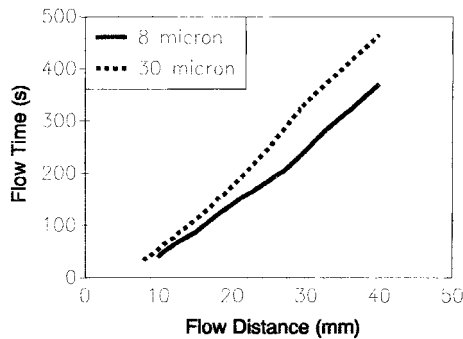


Fig. 3. Flow rate as function of filler particle size (70 wt% filler loading).

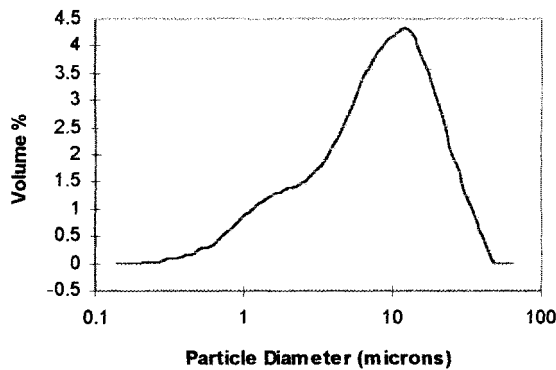


Fig. 4. Particle size distribution (average size approximately 8 μm).

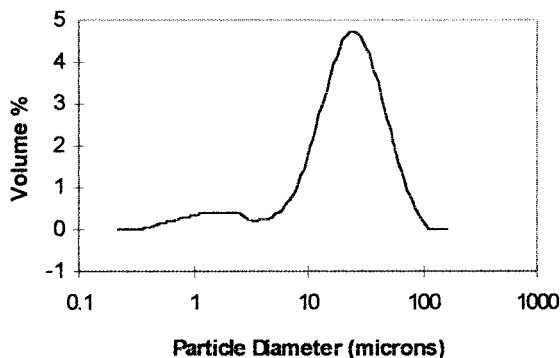


Fig. 5. Particle size distribution (average size approximately 30 μm).

by Goto and Kuno [9]. Fig. 3 shows that faster flow is obtained with a sample of 8 μm average particle size compared to that of a 30 μm average particle size. The discrepancy in these results compared with the reported literature could be from obstruction effects due to the small gap to particle diameter ratio. The average particle size for the 30 μm sample is 30 μm but the distribution (Fig. 5) shows that there are particles present as large as the gap size (75 μm) of the test vehicle. This can cause obstruction effects during the flow. The filler materials used in this study have a broad distribution. Figs. 4 and 5 show the particle size distributions given by a Mastersizer Particle Analyzer by Malvern Instruments, Inc. Also, the SEM photograph (Fig. 6) shows the particle distribution for the 8- μm sized silica. (The 30 μm silica sample gives a similar picture). A broader distribution was used because the flow is improved with mixtures of particle sizes than with monosized

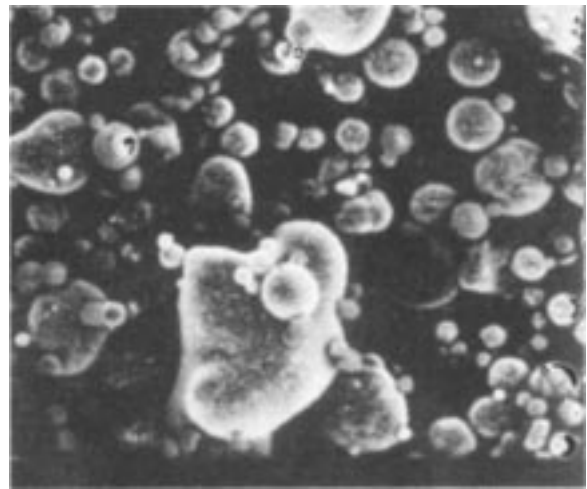


Fig. 6. SEM of dry filler prepared on slide (average size approximately 8 μm).

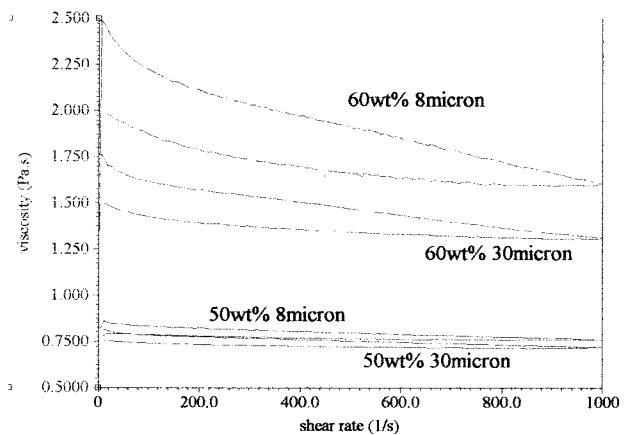


Fig. 7. Viscosity as a function of filler loading and filler size.

particle sizes. It has been reported for particles during capillary flow that multimodal particle size distributions can be used to enhance the flow properties of filled systems [9], [10]. Adding a small amount of the smaller particles brings about a decrease in viscosity of the suspension of larger particles [2]–[5].

B. Viscosity

It is shown in Fig. 7 that the viscosity increases with increasing filler loading. It has been reported in literature that an increase in viscosity occurs as the fraction loading of particles increase [7], [8]. Also, the effect of increasing loading of filler in underfill encapsulants has been shown to decrease the flow rate [4]. This graph also shows that the underfill is shear thinning. Particle size also shows to have an affect on the viscosity. At both loadings, the 8 μm average sized filler showed a higher viscosity compared to that of the 30 μm average sized filler. This seems to contradict the results found from the parallel glass flow test. This contradiction can be described by two different driving forces for the increase in viscosity. In the parallel glass flow test, as the average particle size increases, the maximum particle size also increases. These larger particles are close to the size of the gap and therefore

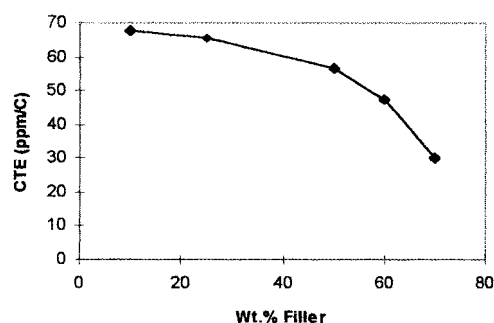


Fig. 8. CTE as function of filler loading (15 μm average particle size used for each sample).

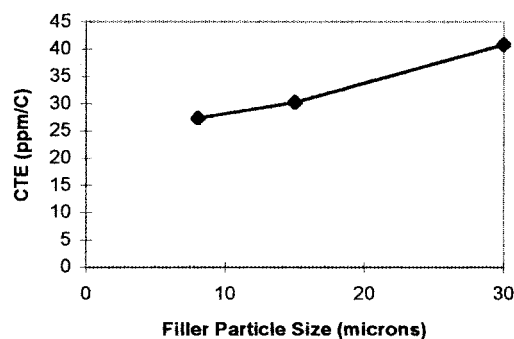


Fig. 9. CTE as function of filler particle size.

friction with the chip and substrate surfaces cause a decrease in flow. For the viscosity found by the rheometer, the increase in viscosity with decreasing particle size is brought about by the interaction of the resin with the larger surface area of the smaller filler.

C. Coefficient of Thermal Expansion

The epoxy resin/HMPA hardener mixture has a CTE of 87 ppm/ $^{\circ}\text{C}$ and the silica has a CTE of approximately 0.5 ppm/ $^{\circ}\text{C}$. As the ratio of filler to resin increases, the CTE will decrease due to the lower CTE of the filler compared to that of the resin. This decrease can be seen in Fig. 8 which shows CTE as a function of filler loading. This graph also shows that a unit change in loading at high loadings decreases CTE more than a unit change in loading at smaller loadings.

As the filler particle size decreases (at a constant volume % loading), the CTE also decreases (Fig. 9). This can be explained by looking at the total surface area of the filler particles. As shown before, the CTE of the filler is much lower than that of the resin. The interface of the filler particles and the resin matrix constrict the expansion of the matrix. As the surface area of the filler particles increase due to the decrease in particle size, there is an increase in the interface between filler and resin. Therefore, an increase in the constriction of the matrix due to increased surface area allows a decrease in the expansion of the matrix. If a large particle size filler and a small particle size filler (each with a narrow size distribution) were mixed in proportions progressing from 100% large particle size to 100% small particle size, the CTE values should decrease due to the increasing surface area.

D. In-House Formulations versus Industrial Formulation

Using the chip/substrate test vehicle, the commercial underfill showed a flow time of 28.9 s at a CTE value of 37.0 ppm. Formula 1 (in-house formulation) has a lower CTE (30.3 ppm) but a longer flow time (50.1 s). Formula 2 (in-house formulation) has a similar CTE (37.5 ppm) to that of the commercial underfill, but the flow time is significantly less at 17.5 s. Therefore, there is a trade-off between flow time and CTE and the underfill should be selected according to the more important parameter.

IV. CONCLUSION

It has been presented that a low underfill encapsulant CTE value is needed for the flip-chip assembly. It was observed that as filler loading is increased, a lower CTE value is reached. This decrease in CTE is more significant at higher loadings than at lower loadings. This work showed that an increase in filler loading decreases the flow rate of the underfill encapsulant between parallel plates as well as increasing the viscosity. The particle size was also proven to have an effect on CTE and flow rate. As the filler particle size decreased, the CTE decreased. This work showed that as the filler particle size decreases, the flow rate increases. One formulation was developed that has a considerably smaller CTE value but a longer underfill time compared to one of industry's faster fast-flow underfills. Another formulation was developed that has a comparable CTE value to that of the commercial underfill but the flow time was significantly less. This underfill formulation is a good candidate for a new fast-flow underfill encapsulant.

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